What RHIC Experiments and Theory tell us about Properties of Quark-Gluon Plasma ?

Edward Shuryak
Department of Physics and Astronomy,
University at Stony Brook, NY 11794, USA

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Abstract

This brief review summarizes the main experimental discoveries made at RHIC and then discusses their implications. The robust collective flow phenomena are well described by ideal hydrodynamics, with the Equation of State (EoS) predicted by lattice simulations. However the transport properties turned out to be unexpected, with rescattering cross section one-to-two orders of magnitude larger than expected from perturbative QCD. These and other theoretical developments indicate that Quark-Gluon Plasma (QGP) produced at RHIC, and probably in a wider temperature region $T_c < T < 4T_c$, is not at all a weakly coupled quasiparticle gas, but is rather in a strongly coupled regime, sQGP for short. After reviewing two other "strongly coupled systems", (i) the strongly coupled supersymmetric theories studied via Maldacena duality; (ii) trapped ultracold atoms with very large scattering length, we return to sQGP and show that there should exist literally hundreds of bound states in it in the RHIC domain, most them colored. We then discuss recent ideas of their effect on the EoS, viscosity and jet quenching.

1 Two sets of major discoveries made at RHIC

The Relativistic Heavy Ion Collider at Brookhaven is the largest facility dedicated to heavy ion physics, built *to produce and study the properties of new form of matter*, the Quark-Gluon Plasma (QGP). Let me emphasize from the onset that this goal of the RHIC project has been met with widely spread skepticism, especially by people with a high energy physics background. It was argued that even if a large number of quarks and gluons be created at RHIC, it will simply fizzle into a firework of multiple jets and mini-jets, with small (and calculable by pQCD) deviations from a set of independent multiple pp collisions.

RHIC just completed its Run-4, in which a record number of events $\sim 10^9$ per detector was recorded. Obviously our experimental colleagues are eager to have a look at it now. However, let us all make a break from ever contunuing stream of work and have a look back, summarizing what have we learned from the data of Runs 1-3 and recent theory development and comparing it with the original picture we had in mind many years ago.

The goal "to produce QGP" via certain set of signals, new flavor, dileptons and phtons, vector meson melting including J/ψ, together with the name itself, was first formulated in my papers [1]. They followed earlier theoretical ideas that very high temperature QCD should be weakly coupled [2], in which the color charge should not be confined but rather screened [1] (thus "plasma"). So QGP was thought to be a "normal phase" of QCD, and expected to be much simpler in its sturucture than the "QCD vacuum", with its chiral symmetry breaking and (still mysterious) confinement, leading to

thousands of quark bound states filling the particle data tables. It was widely expected (for about 3 decades!) that a simple perturbative approach to QGP properties, similar to that used e.g. for QED plasmas, would adequately describe its properties right from $T = T_c$, at least qualiatively.

But, when one penetrates into the domain never studied before, one may always find quite unexpected things[1]. The same happened at RHIC. Not only the skeptics have been proved wrong about "matter" production and robust collective phenomena seen there, but the whole view of QGP structure underwent a major revision in the last year or so.

I will start with a list of major discoveries [2], which I will group into 2 sets, those related with soft $p_t < 2\,GeV$ and hard $p_t > 2\,GeV$ parts of the observed particle spectra.

Discoveries related with the bulk of secondaries ($p_t < 2\,GeV$): are obviously about the properties of the matter produced. We learned that:
(i) like at CERN, particle composition is quite well equilibrated, including strangeness;
(ii) the multiplicity does not grow very rapidly with energy, as binary scaling for hard collisions would suggest, so there is some coherencey in production;
(iii) the magnitude of the radial flow velocity is reaching about .7 of speed of light, is larger than at SPS and its effect extends to higher $p_t \sim 1.5 - 2\,GeV$.
(iv) Especially impressive are data on the so called *elliptic flow*, observed for non-central (and even rather peripheral) collisions. It is significantly stronger than at CERN.
(v) Both radial and elliptic flows are correctly described by hydrodynamics, including their dependence on collision energy, centrality and – last but not least – the particle type. It gave good quantitative description of about 99% of the spectra for all secondaries[3] (except for the hard part at $p_t > 2\,GeV$), essentially without any parameters other than (lattice-based) EoS.

RHIC collisions are sometimes called the *Little Bangs*, and they are obviously quite different from a fizzle predicted by pQCD.

Discoveries related with the hard tail of the spectra $p_t > 2\,GeV$, naturally came from runs 2 and 3.
(i) Already the first data on high transverse momentum tail of the spectrum, from the second RHIC run, have shown its suppression by a factor ~ 5, exceeding expectations of the naive parton model. Including such initial state effects as Cronin effect, one finds that actual jet quenching is closer to a factor 10 suppression.
(ii) The puzzle became more intense when it was found that even the large p_t particles are emitted very anisotropically in the azimuthal angle.
(iii) Observation of the 2-particle correlations at large p_t have confirmed that in these region (of not-so-large p_t) the secondaries still originated from jets. The shadowing of the away-side jets confirmed the strong quenching, as it also reaches about an order of magnitude suppression .
(iv) Further clarification came from the run 3, when a control experiment with deuteron-gold (dAu) collisions has confirmed that at mid-rapidity[4] the suppression is *not* due to the initial state shadowing, but is instead indeed a final state absorption.

The original intention [4] was to use jet quenching in order to get a kind of a tomographic picture of the QGP cluster. However, the data available so far (up to about $p_t = 12\,GeV$ mostly show that a produced matter is so black – up to 90% of produced jets are absorbed – that only jets from the surface

[1] Recall that this very country was "accidentally" discovered by Columbus, searching only another passage to well known India.

[2] I am certainly not in the position to comment on which experiment was the first on which particular observations, and use more or less random set of data, with a reference to the collaboration. (It is possible to use data from any one of them due to quite remarkable level of consistency between RHIC data.) A real experimental summary done by collaborations are expected soon.

[3] Modulo the remaining disagreement with HBT radii, on the level of 30-40 percents.

[4] The latest dAu data from BRAMS experiment indicate much stronger initial state effects in the forward region, hopefully an expected gluon saturation signal.

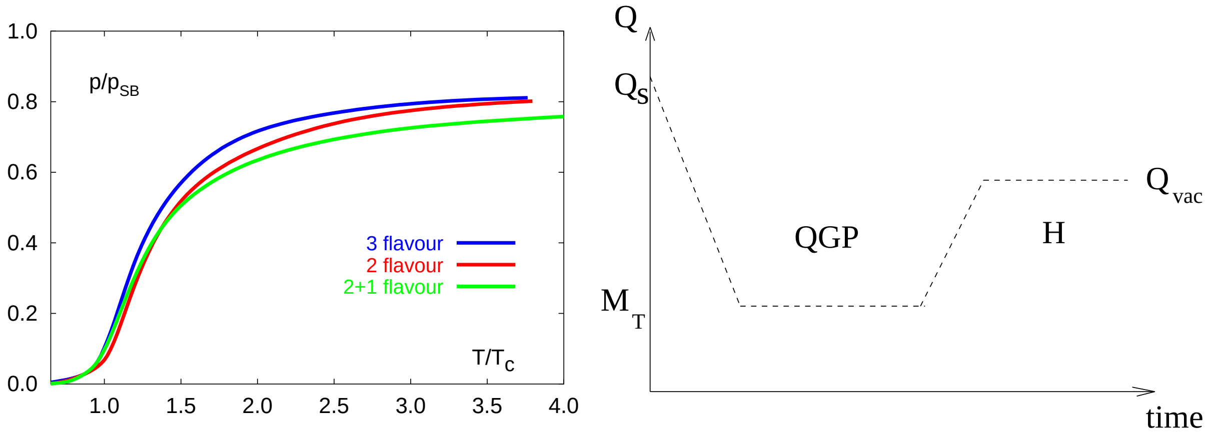

Figure 1: (a) The pressure (divided by that for free gas) versus the temperature T/T_c, from lattice thermodynamics studied by Bielefeld group. (b) Schematic plot of the cut-off scales during the evolution of the system with time, from [15]. At the collision time=0 the scale is presumably the saturation scale Q_s in the incoming nuclei, which grows with the collision energy. Then the cutoff decreases reaching some nearly constant value in QGP at $T > T_c$, the thermal gluon mass M_T (**??**) and stay at this value till it rises again in the mixed phase to its vacuum value in the hadronic (H) phase $Q_{vac} \sim 1\, GeV$.

is escaping. Clearly a drive to larger p_t is still very much needed.

In this brief report I would not discuss the large p_t physics, except of mentioning some new ideas about the mechanism of jet quenching, but will try to summarize in more detail the physics implications of the data at smaller p_t on the QGP production and properties. Before we go into specifics, let me summarize the successes and surprises we have seen on the way.

Brief summary of QGP properties, as it is extracted from data: The thermodynamics at chemical freezeout tells us that it occurs at a universal temperature $T_c \approx 170\, MeV$ which coincides with the expected critical temperature. The hydrodynamics tells us parameters of the EoS: it has not yet been very precisely mapped (we need an energy scan for that), but e.g. the *latent heat* of the QCD transition is fixed by these works to be about 800 MeV/fm^3, the same value as it was predicted by the lattice QCD. Furthermore, the expected EoS (pressure as a function of the energy density) above the transition region is also confirmed to be roughly $p \approx \epsilon/3$.

In contrast to that, the transport properties (viscosity) of QGP turned out to be completely unexpected. The rescattering of constituents needed to sustain the observed degree of collectivity is one to two orders stronger than it was predicted on the basis of pQCD. The ratio of the QGP viscosity relative to its entropy density $\eta/s \sim 1/10$, making it *the most ideal fluid ever observed.* (In particularly: water would not flow, if only few thousends molecules would be put together.)

2 Evolving theoretical views on QGP properties

Since 1970's till quite recently Quark Gluon Plasma (QGP) was viewed as a gas of quasiparticles (dressed quarks and gluons) which interact relatively weakly with each other. A significant amount of theoretical work has been invested on refining the perturbative high-T calculations, to thermodynamics and kinetics of QGP, see e.g. my book [5] for more details. We now know all perturbatively calculable corrections to free gas expressions, $O(g^2, g^3, g^4, g^5, g^6 log(g))$, making in total 7 terms of the weak coupling series (see e.g. [6]). Although they are not converging, unless $T \sim 10^6 GeV$ or so, hopes remained that some clever re-summation will get all the physics right.

The non-perturbative results which came from lattice QCD, such as pressure shown in Fig.1(a), seemed to support this view. Indeed, the ratio of the calculated pressure to that at zero coupling gets

to about 0.8 soon after the phase transition, so it was tempting to assume that the deviation, $\sim .2$, is a good measure of the interaction corrections.

As I will argue below in more detail, this simple reasoning turned out to be very misleading, and it managed to fool us all for decades. Only recently had we learned that in two other examples of very strongly interaction matter – (i) the CFT gauge theory at comparable coupling; and (ii) trapped atoms at the Feshbach resonances – the same ratio also about .8. (And I will argue by the end of this paper, one can explain this .8 for QGP at $T = 2T_c$ in a radically new picture, with only half of pressure coming from a quasiparticle gas and the rest from *hundreds* of bound states.)

The breakthrough in our thinking [27] came basically from 3 different sources:
(i) a general idea that while confinement and chiral breaking disappear at $T > T_c$ and there is not much free charge to generate large Debye mass yet, the sizes of states and scale at which the coupling is defined showld be rather low at $T = (1-2)T_c$, see e.g. Fig.1 (b).
(ii) Triumph of hydro[5] , compared with apparent failure of weak coupling "parton cascades" of various kinds. For example, Gyulassy and Molnar [7] concluded that the elliptic flow can only by reproduced by a gluon cascade if the cross section be enhanced by a factor of about 50. That forced us to think hard *Why is the Quark-Gluon Plasma at RHIC such an ideal fluid ?* Important paper by Policastro, Son and Starinets [19] was a radical step in this direction.
(iii) The last ringing bell came from the lattice practitioners. Surprisingly to all, recent works in Japan and Bielefeld [8] have found that the lowest charmonium states are not melting at T_c, as was believed previously, but actually persist to at least $T = 2T_c$. Then came similar evidences that mesonic bound states made of light quarks survive we into the QGP phase as well [9].

All these developments provided a hint, that the QGP quasiparticles at $T \sim few\, T_c$ have much stronger interaction than previously expected, we have found a *strongly coupled QGP*.

After more details about hydro and brief discussion of two other strongly coupled examples we will return below to recent attempts to understand what exactly sQGP is.

3 Collective flows, EoS and transport properties

Is hadronic matter really produced in heavy ion collisions? Is there something qualitatively new in AA collisions, never seen in "elementary"[6] pp or $e+e-$ collisions?

Indeed, the original motivation for heavy ion program is not just increase the number of secondary particles produced per event (up to several thousands at RHIC), but to reach a *qualitatively different* dynamical regime. characterized by a small microscopic scale l (e.g. mean free path) as compared to the macro scale L (the system's size): $l \ll L$. If this is achieved, the fireball produced in heavy ion collisions should be treated as a macroscopic body, with thermo and hydrodynamics.

Statistical models do indeed work remarkably well for heavy ion collisions, even at energies lower than RHIC. But they also work for pp or e^+e^- (and we still do not know why). end to it. In contrast to that, pp or e^+e^- show no sign of flow effects, see early attempts to see them [10]. So, a multi-body excited systems produced in these case are *not* macroscopically large. It is not "matter" but just a bunch of particles.

[5] In fact the hydrodynamics with its "non-ideal" expansion in powers of the mean free path is the oldest example of a *strong coupling* expansion, including the *inverse* powers of the cross section.

[6] Apart of the large-p_t tail, described by the parton model plus pQCD corrections, it is very far from being elementary and is very poorly understood. One may argue that heavy ion collisions, described well by hydro/thermodynamics, are in fact even much simpler.

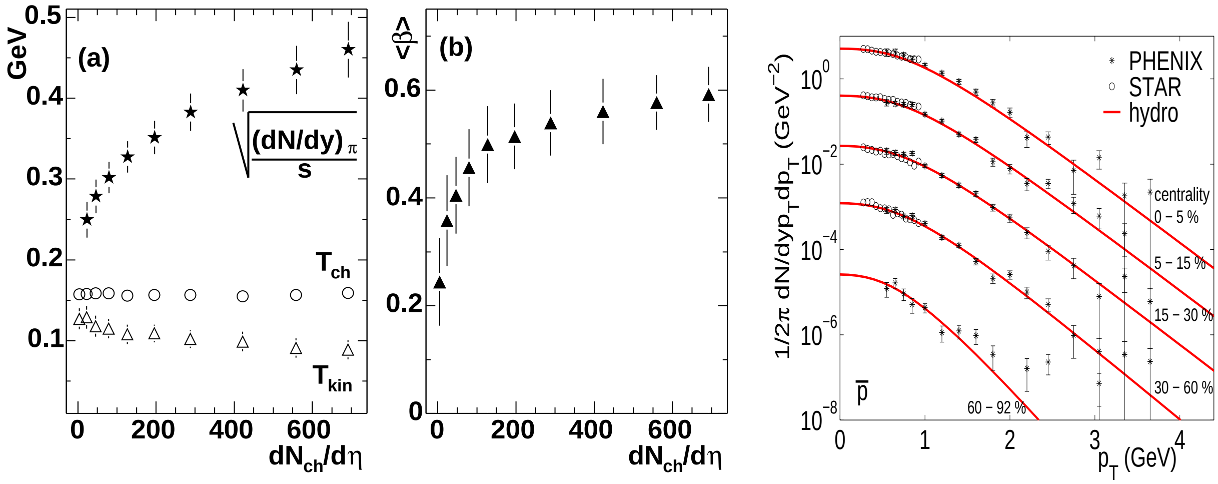

Figure 2: (a) The "blast model" fits to STAR collaboration data. The values of the and freezeout temperatures are shown in (a) and the mean collective velocity. (b) Comparison between STAR and PHENIX data for protons with hydro calculation by Kolb and Rapp [12] (which correctly incorporates chemical freezeout).

3.1 Transverse flow

Heavy ion collisions, on the other hand, showed a variety of *"flows"* since very low energies, but not all of them are indeed a collective expansion.

Let me start with a historic comment. First attempts to connect the experimental information with the collective transverse flow were made independently by Siemens and Rasmussen [11] for low energy (BEVALAC) and by Zhirov and myself [10] for high energy pp collisions at CERN ISR around 1979. The idea of both papers was exactly the same: collective expansion boosts spectra of various secondaries differently, depending on their mass. Pions are light and their spectrum remains exponential, with a "blue shifted" temperature, while for heavy particles the effect is different. Fortunately it is easily calculable and depends on the value of the particle mass only.

Siemens and Rasmussen found the expected difference for pions and protons produced by heavy ions at $E \sim 1GeV/N$ fitted them with two parameters, the freezeout temperature $T_f \sim 30\,MeV$ and the velocity of what they have called the "blast wave". (Long discussion afterwords shown that ideal hydro is not really applicable in this case, however.). Zhirov and myself [10] found no flow in pp data from ISR: the $\pi, K.N$ spectra from pp showed the same m_t-slope. All of us had to wait for heavy ion collisions at high energies, and only at SPS and now at RHIC we have seen real hydrodynamical flow, radial and especially elliptic.

Let me jump years ahead and show a modern version of the blust wave fit to RHIC data, shown in Fig.2 as a function of centrality. Two basic parameters are the freezeout temperature T_{kin} and the mean flow velocity $< \beta >$. T_{kin} decreases and the velocity increases for more central collisions, displaying an expected conversion of the internal energy into flow. Note also that the temperature of chemical equilibration T_{ch} seem to be completely independent of the centrality: the interpretation of it is that it is in fact the *QCD critical temperature*.

Fig.2 is an example of a hydro prediction for the proton p_t spectra. Note that no parameters (other than total entropy and EoS) are used, and the agreement of the predicted shape is very good, both in normalization and shape.

At RHIC (rather unexpectedly) we found that different flow-related slopes for pion and nucleons holds till rather large $p_t \sim 2\,GeV$, making both spectra to cross. As a result there are more baryons than pions above this point (till about $p_t \sim 5\,GeV$). Observation of that lead to a very good question:

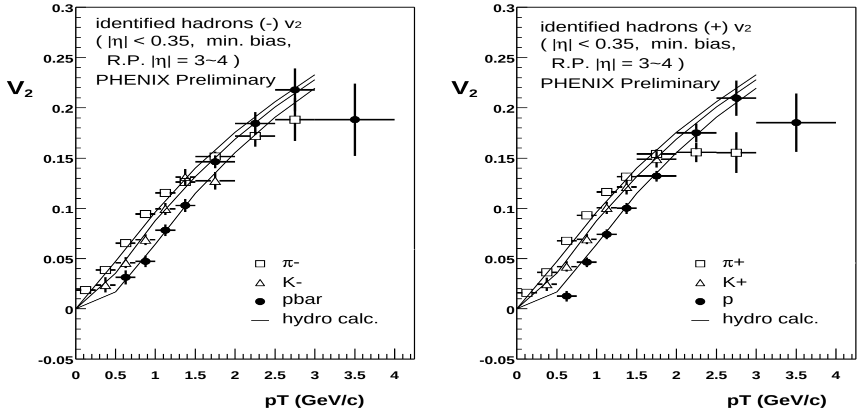

Figure 3: The p_t-differential elliptic flow $v_2(p_t)$ from minimum bias Au+Au collisions at RHIC, for different identified hadron species (PHENIX). with negative (left) and positive (right) charge.The curves are hydrodynamic calculations.

how far down the spectrum the hydrodynamics should be trusted?

3.2 Elliptic Flow

Non-central heavy ion collisions produced fireball which has an almond shape. It would not matter for independently produced secondaries, but in a collective expansion the shape matters, leading to "elliptic" flow pattern. This is quantified by v_i harmonics defined as

$$\frac{dN}{d\phi} = \frac{v_0}{2\pi} + \frac{v_2}{\pi}\cos(2\phi) + \frac{v_4}{\pi}\cos(4\phi) + \cdots \tag{1}$$

Each of v_i is a function of centrality (the impact parameter b), rapidity y, transverse momentum p_t and, last but not least, the particle type. By now v_1, v_2, v_4 have been studied. The important feature of elliptic flow is *self-quenching*, as a result of which the elliptic flow develops earlier than the radial one. This is why it is especially important for understanding the EOS of the QGP.

The ellipticity depends on a particle mass, again in a predictable way [13]. Let me show few plots from Kolb and Heinz review [14] to convince the reader that the elliptic flow is a hydrodynamical effects.

The next Fig.4 makes use of one important fact: centrality dependence of v_2 is basically a response to the initial *spatial* anisotropy of the system, quantified by the parameter $\epsilon = \langle y^2 - x^2\rangle / \langle y^2 + x^2\rangle$, and so plotting v_2/ϵ one basically eliminates the geometry of the problem and finds all points at some universal curve, see[7] Fig.4(a).

The main message of this figure is that v_2 grows with multiplicity[8] . The parts (b,c) of the figure shows how the v_2 magnitude was expected to depend on the collision energy[9], from Teaney et al [13].

We will not have time to discuss details of the hydrodynamics calculations, which reproduce these data. Let me only tell why RHIC energy range is special. Due to the QCD phase transition, the matter is very soft in the so called "mixed phase" energy density region. That is why at SPS energies there was no substantial v_2 contribution, which only happen at RHIC due to "stiff QGP".

[7]The horisonal band on this figure marked "hydro limit" refers to some hydro with ideal gas EoS and simplistic freezeout. It supposed to hold at very large entropy density.

[8]This theoretical prediction was made at QM99 by Teaney and myself, as well as Kolb and Heinz, prior to RHIC.

[9]Other authors such as Ollitraught and Heinz et al have used fixed freezeout predicted a different energy dependence of v_2.

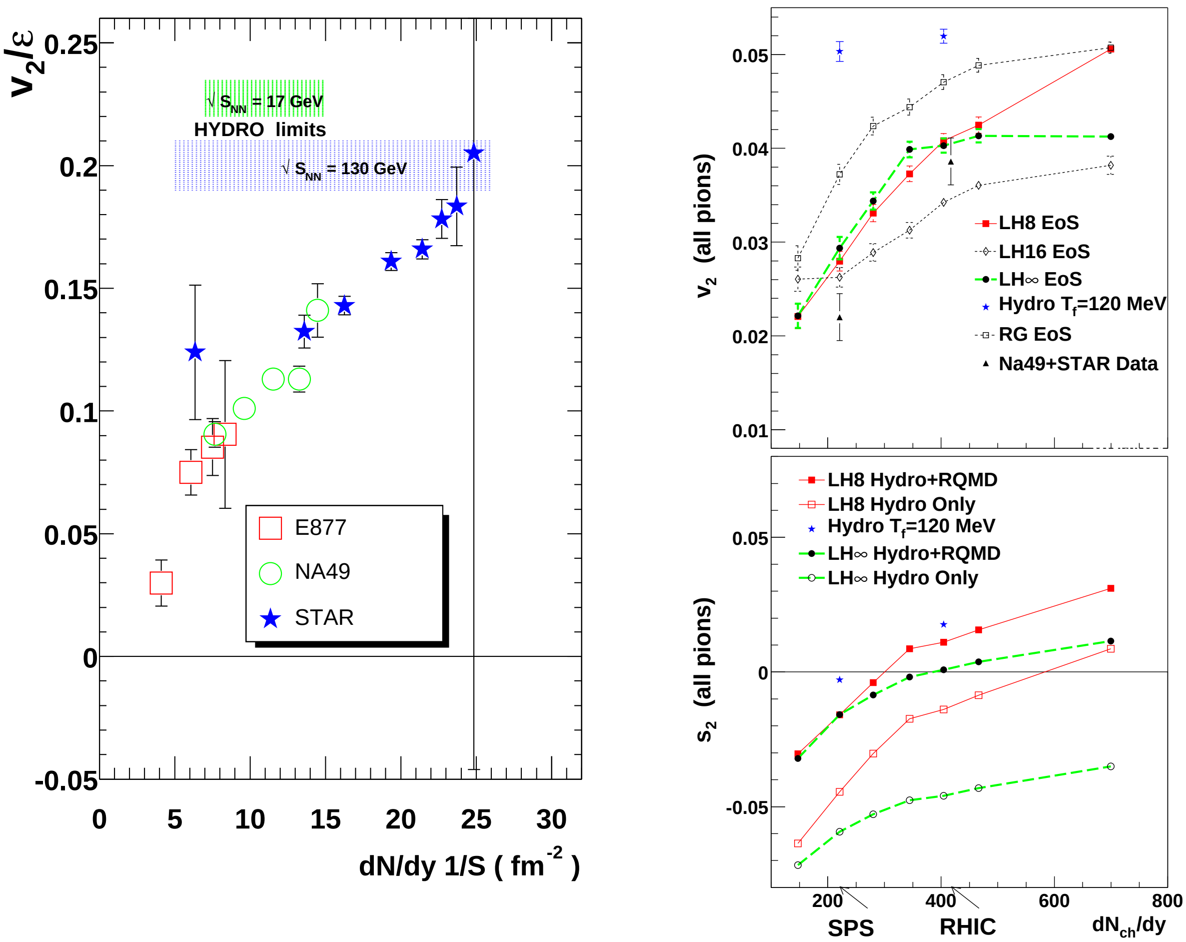

Figure 4: (a) The compilation of elliptic flow (the ratio of v_2/ϵ) dependence on collision energy (represented by the particle multiplicity). (b,c) Energy dependence of the elliptic flow predicted by hydro calculation by Teaney et al [13] for different EoS. The curve with the latent heat (LH) =800 MeV/fm^3 is the closest to the lattice EoS, and it is also the best fit to all flow data at SPS and RHIC

3.3 The limits to ideal hydro

The ideal hydrodynamics is *not* just a bunch of conservation laws, but the local parameterization of the stress tensor

$$T^{\mu\nu} \quad = \quad (\epsilon + p)u^\mu u^\nu - p g^{\mu\nu} \tag{2}$$

Here ϵ is the energy density, p is the pressure, and $u^\mu = \gamma(1, \mathbf{v})$ is the proper velocity of the fluid.

Inclusion of dissipative effects, to the first order in l/L, is possible via the following corrections to the stress tensor

$$\delta T_{\mu\nu} = \eta(\nabla_\mu u_\nu + \nabla_\nu u_\mu - \frac{2}{3}\Delta_{\mu\nu}\nabla_\rho u_\rho) + \xi(\Delta_{\mu\nu}\nabla_\rho u_\rho) \tag{3}$$

where the coefficients η, ξ are called the shear and the bulk viscosities. In this equation the following projection operator onto the matter rest frame was used: $\nabla_\mu \equiv \Delta_{\mu\nu}\partial_\nu$, $\Delta_{\mu\nu} \equiv g_{\mu\nu} - u_\mu u_\nu$. It is further useful to normalize the magnitude of the viscosity coefficient η to the entropy density s, forming a dimensionless ratio. For example a sound wave have dispersion law

$$\omega = c_s q - \frac{i}{2}\mathbf{q}^2\Gamma_s, \qquad \Gamma_s \equiv \frac{4}{3T}\frac{\eta}{s} \tag{4}$$

Let us now discuss what is the value of QGP viscosity, following Teaney [16]. He argued that relative deviations from ideal case should be $\sim (\eta/s)p_t^2$, and shown that such deviations are indeed seen in real data. In Fig.5 we show it for the elliptic flow parameter v_2. Since its value is determined at sufficiently early times – about 3 fm/c – the deviation should correspond to the QGP phase. The results for different Γ_s/τ shown in Fig.5 deviate from ideal hydro curve at $p_\perp \approx 1.6\,GeV$ which indicates $\Gamma_s/\tau \sim 0.05$ or so. Substituting here the relevant time $\tau \sim 3fm/c$ we get $\Gamma_s \sim .15fm$. Strong coupling result for typical $T \sim 200\,MeV$ at the time gives $\Gamma_s \sim 0.1fm$, while weak coupling one would predict much larger value $\Gamma_s \sim 2fm$ or so. About the same value follows from the gluon cascade with the enhance cross section by Molnar and Gyulassy [7] mentioned above.

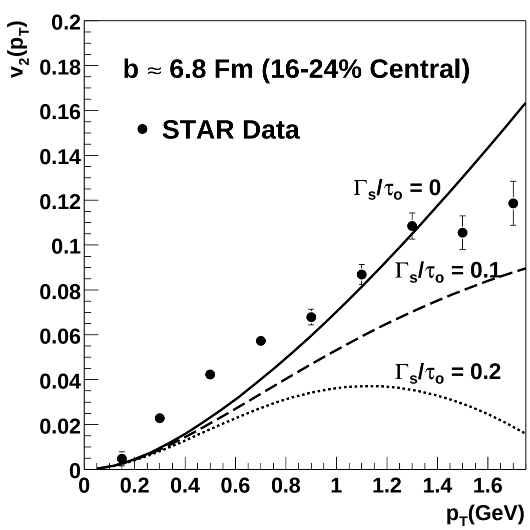

Figure 5: Elliptic flow v_2 as a function of p_T for different values of Γ_s/τ_o. The data points are four particle cumulants data from the STAR collaboration. Only statistical errors are shown.

4 Other strongly couples systems

4.1 Finite T $\mathtt{N}$ =4 supersymmetric gauge field theory at strong coupling

To find a gauge theory in which strong coupling limit makes sense is a nontrivial task. Furthermore, to develop tools which would allow a systematic expansion in *inverse* coupling constant is even more challenging. However both problems have been solved during 1990's, first for a specific – 4 times supersymmetric – gauge theory, and then for some other examples (we would not discuss).

It is a Conformal Field Theory (CFT), with a non-running coupling. Its finite-T version is in the QGP-like phase at *any* coupling, from weak to strong. As a result of long development by string theorists based on "holography" and "duality" ideas, the so called AdS/CFT correspondence [17] was shown, which states that *CFT in strong coupling is dual to a weakly coupled string theory*, albeit in 10 dimensions in a particular gravity field. The finite-T version has a gravity metrics with a *black hole*, and it is its Howking radiation which heats up our Universe[10], represneted by a 4-d surface at some distance from the black hole.

For a non-string theorist like myself to follow the duality arguments and gravity-based arguments is a fascinating, near magical experience. On the other hand, as I am not really interested in string theory and consequences of supersymmetry, but rather in generic effects of any strong coupling, it is imperative to find a meaning for gravity-based calculations and results *inside the gauge theory itself.* This work has just started (see below) and we of course have a lot of problems to solve.

This CFT has gluons with N_c colors, which for technical reasons is considered large, 4 types of fermions (gluinos) and 6 scalars. The gauge coupling is always combined with the color factor $\lambda \equiv g^2 N_c$, and can be either small or large. In the former case one has standard Feynman calculus on a gauge side, in the latter it is better to used the gravity formulation. For instance, a potential between two static quark-like charges is then described by a string between them, which is not straight as in QCD but stretched by gravity into 5-th dimension. The result is a modified Coulomb's law for strong coupling ($\lambda \gg 1$) [17], which has the same r-dependence but $\sqrt{\lambda}$ instead of λ

$$V(r) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{r} \tag{5}$$

times a very strange coefficient including Euler Gamma function.

The strong-coupling results for finite T include:

(i) bulk thermodynamics resulted in[18] It was found that the free energy in this limit is $\mathbf{F}(T, N_c, \lambda) = \Big((3/4) + O(1/\lambda^{3/2})\Big)\,\mathbf{F}(T, N_c, 0)$ where $\mathbf{F}(T, N_c, 0) \approx N_c^2 T$ is the free (zero coupling) result, analogous to Stephan-Boltzmann result for blackbody radiation.

(ii) the heavy quark potential is totally screened for a Debye radius of order $1/T$ [20] and leads to quasiparticle masses of the order $M \sim \sqrt{\lambda}T$

(iii) viscosity of strongly coupled matter was found to be unusually small, leading to a rather good liquid with hydrodynamical behavior even at small spatial scales. In particular, the viscosity to entropy ratio was found to be [19]

$$\frac{\eta}{s} = \frac{1}{4\pi} \tag{6}$$

which is probably the smallest possible value, as it is obtained for an infinite coupling.

One thing that became clear to us [21] is the meaning of the black hole. Thinking about strongly coupled gauge theory one cannot aviod noticing that in particular partual waves particles fall at each

[10] As Sun worms the Earth.

other, propagating indefinitely toward small distances. This for example happens in Klein-Gordon eqn. for $\alpha > 1/2$. In equilibrium, there must also be waved propagating back, from small to large distances: this constant pair production is a kind of Hawking radiation.

Another is that the ineteraction is transfered by gluons with a superluminal speed, $v \sim \lambda^{1/4} >> 1$, which may justify potential type ladder diagrams even for relativistic bound states.

Ferthermore, as I will try to show, it explained the puzzle of why thermodynamics can be nearly independent on the value of the coupling λ in strong coupling, while the composition of matter drastically changes when it changes from weak to strong. In a naive picture of a quasiparticle gas, one would expect the Boltzmann factors for quasiparticles to be $exp(-M/T) \sim exp(-\sqrt{\lambda}) \ll 1$, while $p \sim T^4$ clearly demands the light particles with masses $M \sim T$ at any coupling. What those states may be?

Zahed and myself [21] proposed an explanation: these light states are deeply bound binary composites, in which the supercritical Coulomb is balanced by the centrifugal force. The argument is rather involved and cannot be given here. Let me just say that the key is the derivation of the modified Coulomb law via ladder diagrams is possible, revealing that virtual gluons in this regime must fly with super-luminal velocity $v \approx \lambda^{1/4} \gg 1$. Therefore even for relativistically moving quasiparticles the interaction can be described by a potential. Solving the Klein-Gordon (or Dirac or Yang-Mills) equations for scalars (or spinors or gluons) in yields **towers of deeply bound states**, extending from large quasiparticle masses $m/T \approx \sqrt{(\lambda)}$ all the way to small ones $E/T \approx \lambda^0$ that are independent of the coupling constant. More specifically the spectrum is

$$E_{nl} = \pm m \left[1 + \left(\frac{C}{n + 1/2 + \sqrt{(l+1/2)^2 - C^2}} \right)^2 \right]^{-1/2} . \tag{7}$$

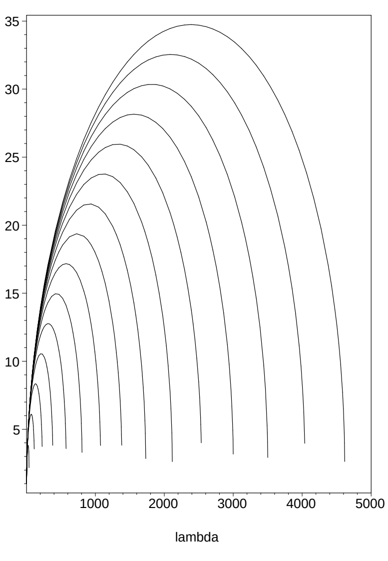

Figure 6: The spectrum of the states versus the 'tHooft coupling constant λ. for the levels with fixed $n_r = 0$ and the orbital momentum $l = 1..15$. One can see that there are light bound states at any coupling.

In weak coupling $C = g^2 N = \lambda$ is small and the bound states energies are close to $\pm m$. Specifically [11] $E_{nl} - m \approx -\frac{C^2 m}{2(n+l+1)^2}$, which is the known Balmer formulae. All of that, including the expression above, was known since 1930's.

New view on this formula, in the (opposite) strong coupling limit, gives the following. If the Coulomb law coefficient is large $C = (4\pi^2/\Gamma(1/4)^4)\sqrt{\lambda} \gg 1$, the quantized energies are imaginary *unless the square root gets balanced by a sufficiently large angular momentum.* In this regime, one may ignore the 1 in (7) and obtain the **equi-distant** spectrum of deeply bound states

$$E_{nl} \approx \frac{m}{C} \left[(n + 1/2) + \left((l + 1/2)^2 - C^2 \right)^{1/2} \right] \tag{8}$$

Rather unexpectedly, we have also found that even though the trajectory of any particular Coulomb bound state depends critically on the coupling λ, their average density remains about λ-independent constant. This explains puzzling results obtained using the string theory. Although each level energy, and even its existsnce, depend on the coupling, the partition function is nearly independent of it.

[11] The fact that only the combination $n + l$ appears, i.e. principle quantum number, is a consequence of the known Coulomb degeneracy. This is no longer the case in the relativistic case.

5 Strongly coupled trapped atoms

If the previous section is too theoretical to some readers, here is a table-top experiment. Exciting recent development took place at the frontier of low temperature physics, with trapped Li^6 (fermionic) atoms. Using magnetic field one can use the so called Feshbach resonances and make a pair of atoms nearly degenerate with their bound state (usually called a molecule but actually a Cooper pair). This results in so large scattering length a, than a qualitatively new type of matter – *strongly coupled fermi and bose gases* – is observed. In particular, this very dilute systems start to behave hydrodynamically, displaying elliptic flow very similar to that in non-central heavy ion collisions.

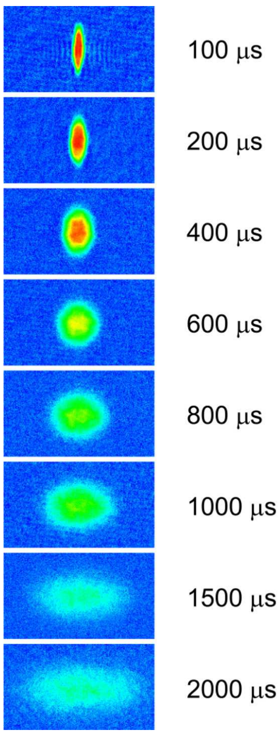

Figure 7: Hydrodynamical expansion of trapped Li^6, from [22].

More generally, studies of strongly coupled many-body problems, in which the binary scattering length diverges, is being studied in at least two other settings: (i) a dilute gas of neutrons, with the famous virtual level; (ii) trapped atomic Li atoms in which the scattering length can be tuned till practically infinite values, plus or minus, by applying a magnetic field which shifts the Feshbach resonances.

Remarkably, for its fermionic version it was indeed found very recently that a strong coupling leads to a hydrodynamical behavior [22]. The way it was demonstrated is precisely the same "elliptic flow" as discussed above. One can start with a deformed trap. Normally the gas is so dilute $an^{1/3} \ll 1$ that atoms just fly away isotropically, but when tuning to strong coupling regime is done the expansion is anisotropic and can be described hydrodynamically.

A number of other spectacular experimental discoveries with trapped Li^6 were also made later. It was found [23] that an adiabatic crossing through the resonance converts nearly all atoms into very loosely bound (but remarkably stable) "Cooper pairs", which can also Bose-condense [24] if the temperature is low enough. Since in heavy ion collisions the system also crosses the zero binding lines adiabatically, various bound pairs of quarks and gluons should also be generated this way. That is probably why we do not observe large fluctuations predicted for systems crosseing the QGP-hadronic matter boundary.

6 New picture of QGP, with multiple bound states

Deconfinement was expected to guarantee that no hadronic bound states would survive at $T > T_c$, except perhaps $\bar{b}b$ states bound by color Coulomb forces. The earliest suggested QGP signal was a disappearance of familiar hadronic peaks – ρ, ω, ϕ mesons – in the dilepton spectra [1]. Moreover, even small-size deeply-bound $\bar{c}c$ states, $\eta_c, J/\psi$, were expected to melt at $T \approx T_c$ [25, 26]. However, as we already mentioned in the Introduction, there are indications from the lattice that charmonium and light quarks do create meson-like states at $T > T_c$.

In the first paper by Zahed and myself on the issue[27] we related presence of loosely bound pairs of quasiparticles with large rescattering and hydro regime of QGP[12]. Indeed, the scattering lengths are supposed to diverge at the *zero binding lines* on the phase diagram (see Fig.8(a)), introduced in [27]. Those line are separate sQGP from wQGP, in which there are no bound states.

[12]We suggested this mechanism for large rescattering before we learned about Feshbach resonances for atoms, which proves that this mechanism works.

channel	rep.	charge factor	no. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + \bar{q}g$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$4_s * N_f^2$
$qq + \bar{q}\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$

Table 1: Binary attractive channels discussed in this work, the subscripts s,c,f mean spin,color and flavor, $N_f = 3$ is the number of relevant flavors.

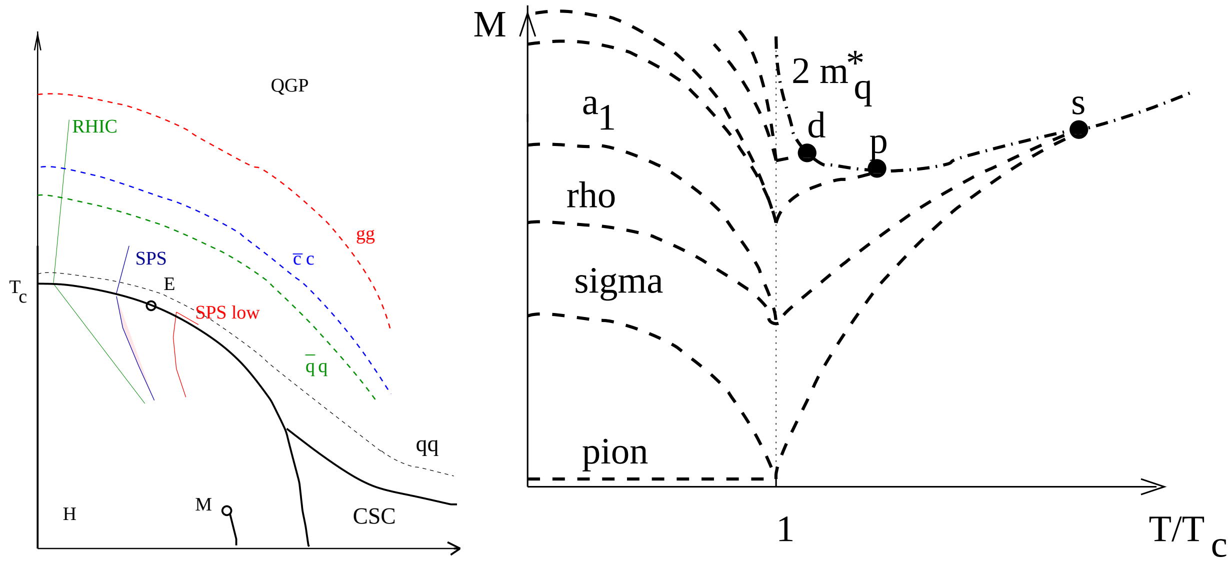

Figure 8: Schematic position of several zero binding lines on the QCD phase diagram (a) and of specific hadronic masses on temperature T (b). In the latter the dash-dotted line shows twice the (chiral) effective mass of a quark. Black dots marked s, p, d correspond to the points where the binding vanishes for states with orbital momentum $l = 0, 1, 2....$

In our paper [29] we investigate the relationship between four (previously disconnected) lattice results: **i.** spectral densities from MEM analysis of correlators; **ii.** static quark free energies $F(R)$; **iii.** quasiparticle masses; **iv.** bulk thermodynamics $p(T)$. We found high degree of consistency among them not known before. The potentials $V(R)$ derived from $F(R)$ lead to large number of binary bound states, mostly colored, in gq, qq, gg, on top of the usual $\bar{q}q$ mesons. Using the Klein-Gordon equation and (**ii-iii**) we evaluate their binding energies and locate the zero binding endpoints on the phase diagram, which happen to agree with (**i**). We then estimate the contribution of all states to the bulk thermodynamics in agreement with (**iv**).

The bound states of $\bar{q}q$ can only be colorless mesons (the octet channel is repulsive), but in QGP there can be *colored* bound states. Quite famous are quark Cooper pairs qq which drive the color superconductivity at sufficiently high density and low T: but pairs themselves should exist outside this region as well. Gluons can form a number of states with attraction, and there can also be gq hybrids. A generic reason why we think all of them exist is that at T close to T_c all quasiparticles are very heavy.

Using a singlet $\bar{q}q$ as a standard benchmark (the only one studied so far on the lattice), one can summarize the list of all attractive channels in the following small Table1, indicating the relative strength of the Coulomb potential and also a number of states. One can see, there are many hundreds of attractive channels which can support bound states.

In another paper, by Brown et al [28], the fate of the $\bar{q}q$ bound states is traced to $T \approx T_c$, where

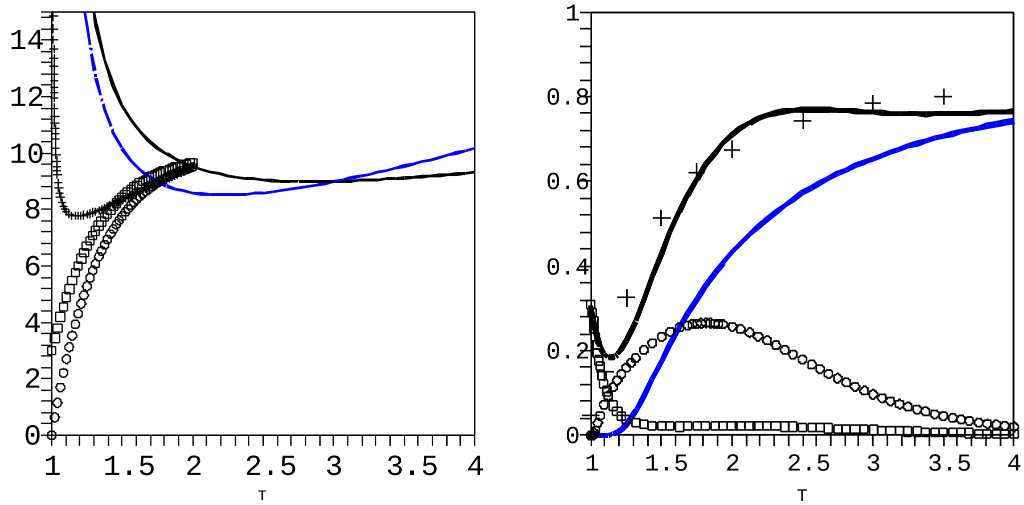

Figure 9: (a) The lines show twice the effective masses for quarks and gluons versus temperature T/T_c. Note that for $T < 3T_c$ $M_q > M_g$. Circles and squares indicate estimated masses of the pion-like and rho-like $\bar{q}q$ bound states, while the crosses stand for all colored states. (b) Pressure (in units of that for a gas of massless and noninteracting quasiparticles) versus the temperature T/T_c. The crosses correspond to the $N_f = 2$ lattice results, from Fig.1(a). The lower solid curve is the contribution of unbound quasiparticles, the upper includes also that of all bound states. Squares are for the pion-like and rho-like $\bar{q}q$ bound states combined, and circles for all the colored bound states.

the Nambu-Goldstone and Wigner-Weyl modes meet. The pion binding at total zero mass is very difficult to reach from the sQGP side, and it can only be accomplished by the combination of (i) the color Coulomb interaction, (ii) the relativistic effects, and (iii) the interaction induced by the instanton-anti-instanton molecules. The spin-spin forces turned out to be small. While near T_{zb} all mesons are large-size nonrelativistic objects bound by Coulomb attraction, near T_c they get much more tightly bound, with many-body collective interactions becoming important and making the σ and π masses approach zero (in the chiral limit). The wave function at the origin grows strongly with binding, and the near-local four-Fermi interactions induced by the instanton molecules play an increasingly more important role as the temperature moves downward toward T_c.

With all of it included, Zahed and myself [29] had evaluated the contribution of all these binary bound states into the partition function. The results for masses of the bound states are shown in Fig.9(a), and the resulting pressure in Fig.9(b). We have shown that as the level closes toward its endpoint, its contribution to pressure becomes partially compensated by a repulsive effective interaction between the unbound quasiparticles. The contribution of the virtual level above zero quickly disappear. Assembling all these ingredients together, we have found that all pieces fit together nicely, reproducing total pressure as calculated on the lattice. Hundreds of exotic bound states are tamed by small Boltzmann factors, contributing (at RHIC) up to about a half of the pressure.

Quite recently we have noticed [30] one more important role that binary bound states may play in sQGP: "ionization" of them by passing jets can contribute to jet quenching. Indeed, in QED we know it to be dominant at not-too-large gamma factors $\gamma = 1 - 100$. One motivation is that at SPS the density is not that much different from RHIC, and yet there is no jet quenching. One obvious difference with radiative mechanism is that the lost energy is *not* to be found in the forward cone.

7 Brief summary and outlook

There is no question that with the RHIC project we got very lucky: we have not found exactly what we expect, but got instead much more. RHIC experiments have shown that the QGP at $T = (1-2)T_C$ is not a weakly interacting gas of quasiparticles, being instead a *strongly coupled QGP*.

Not only the expected energy density is reached, as planned well above the critical region, but we have indeed created a *well-equilibrated matter*, behaving as it should in a bulk. Surprisingly, this is true not only for most central collisions, but also for relatively peripheral ones (but not most peripheral, of course). That means that few hundred of particles is already enough, even for very specific hydrodynamical effects like elliptic flow. This is truly surprising: it would not work for a small drop containing only few hundreds of water molecules!

What exactly sQGP is we start to understand only now. A lot of experience with two other strongly coupled systems was emphasized in this summary: those are (i) ultra-cold trapped cold atoms in a large scattering length regime; and (ii) the N =4 supersymmetric Yang-Mills theory, or CFT. Both show that strong coupling does indeed lead to a hydrodynamical behavior and small viscosity. Both teach us a lesson, that small deviation of EoS from ideal gas does not really mean the matter is weakly interacting. Both show that resonances between bound and unbound states seem to play a key role in hydro flow.

The next notable theoretical achievement is that quantitative predictions of lattice QCD, on T_c value, the magnitude of the "latent heat" and also overall EoS were justified by data. Together with hydrodynamics (and details like knowledge of the initial shape of the overlap region and final freezeout conditions) it provided essentially parameter free theory, which was exactly on the mark as far as all flows (spectra) are concerned. (I think the remaining discrepancies with HBT radii will be worked out.)

There are plenty of other open questions and even known experimental puzzles. Is charm floating with all other flavors, or not? What happens with charmonium, is it enhanced or depleted? Why are there so many baryons at $p_t = 2-5\, GeV$? Why the ellipticity is so large even at very large $p_t \sim 10 GeV$? Can we see some of the bound states in sQGP in a dilepton signal? What role the bound state play in jet quenching?

And a super-question is: which part of what we have learned at RHIC would still be applicable at LHC? Will it still be a bang, or not? Stay tuned...

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